

Suzaku and Fermi Observations of Gamma-Ray Bright Radio Galaxies: Origin of the X-ray Emission and Broad-Band Modeling

Y. Fukazawa, S. Tokuda, R. Itoh, Y. Tanaka

Department of Physical Science, Hiroshima University; Hiroshima Astrophysical Science Center, Hiroshima University

J. Finke

U.S. Naval Research Laboratory

L. Stawarz

Institute of Space and Astronautical Science, JAXA; Astronomical Observatory, Jagiellonian University

We performed a systematic X-ray study of eight nearby γ -ray bright radio galaxies with *Suzaku* for understanding the origin of their X-ray emissions. The *Suzaku* spectra for five of those have been presented previously, while the remaining three (M 87, PKS 0625–354, and 3C 78) are presented here for the first time. Based on the Fe-K line strength, X-ray variability, and X-ray power-law photon indices, and using additional information on the [O III] line emission, we argue for a jet origin of the observed X-ray emission in these three sources. We also analyzed five years of *Fermi* Large Area Telescope (LAT) GeV gamma-ray data on PKS 0625–354 and 3C 78 to understand these sources within the blazar picture. We found significant γ -ray variability in the former object. Overall, we note that the *Suzaku* spectra for both PKS 0625–354 and 3C 78 are rather soft, while the LAT spectra are unusually hard when compared with other γ -ray detected low-power (FRI) radio galaxies. We demonstrate that the constructed broad-band spectral energy distributions of PKS 0625–354 and 3C 78 are well described by a one-zone synchrotron/synchrotron self-Compton model. The results of the modeling indicate lower bulk Lorentz factors compared to those typically found in other BL Lac objects, but consistent with the values inferred from modeling other LAT-detected FRI radio galaxies. Interestingly, the modeling also implies very high peak ($\sim 10^{16}$ Hz) synchrotron frequencies in the two analyzed sources, contrary to previously-suggested scenarios for FRI/BL Lac unification. We discuss the implications of our findings in the context of the FRI/BL Lac unification schemes.

1. Introduction

This contribution is based on Fukazawa et al. [2015]. Here, we very briefly describe the digest. *Fermi* Large Area Telescope (LAT) established that radio galaxies are bright gamma-ray emitters [Abdo et al. 2010]. However, inner jet emission has been detected mainly in the radio and GeV gamma-ray band for most object, due to bright stellar and accretion disk components in the optical and X-ray band; Spectral Energy Distribution (SED) of jet emission is often unclear, even for Cen A and NGC 1275. Thus, X-ray detection of jet emission is important for SED modeling.

Suzaku X-ray satellite has observed 8 nearby GeV-emitting radio galaxies listed in Abdo et al. [2010]; some of observations are originally proposed by ourselves. Most of *Suzaku* results has been published, and some of them exhibit a Fe-K line (3C 111, 3C 120, NGC 1275, Cen A) and others do not (NGC 6251, M 87). Here we report *Suzaku* and *Fermi* results on PKS 0625–354 and 3C 78 [Fukazawa et al. 2015].

2. X-ray Results

Figure 1 shows *Suzaku* X-ray spectra of PKS 0625–354 and 3C 78. Quality of X-ray spectra are better than ever for both objects. We fitted their spectra by one or two plasma model plus power-law

model. The former represents a soft thermal emission associated with host galaxies. The spectra are well fitted by this modeling, and the power-law photon index is 2.25 ± 0.02 and 2.32 ± 0.04 for PKS 0625–354 and 3C 78, respectively. This value is relatively larger for Seyfert galaxies whose X-ray emission is dominated by disk/corona emission. Fe-K line is not detected for both; an upper limit of equivalent width (EW) of Fe-K line is 7 eV and 75 eV for PKS 0625–354 and 3C 78, respectively. X-ray time variation during one *Suzaku* observation is weak or little. We compared X-ray properties with those of Seyfert galaxies, together with other GeV-emitting radio galaxies. Fe-K line EWs of PKS 0625–354, 3C 78, M 87, NGC 6251 are smaller than those of typical Seyfert galaxies as shown in figure 2. Fe-K line is emitted when the X-ray emission from the central disk/corona region is reflected by the dust torus with a large reflection angle. Therefore, a weak or no Fe-K line indicates that the X-rays are not a disk/corona emission but likely a beamed jet emission. X-ray luminosity of PKS 0625–354 is higher than that of typical Seyfert galaxies with a similar [O III] luminosity. Combined with studies of other X-ray properties, such as spectral index, variability, X-ray emission of low excitation radio galaxies (LERG), which are considered to have a low mass accretion rate, is likely to be a jet emission.

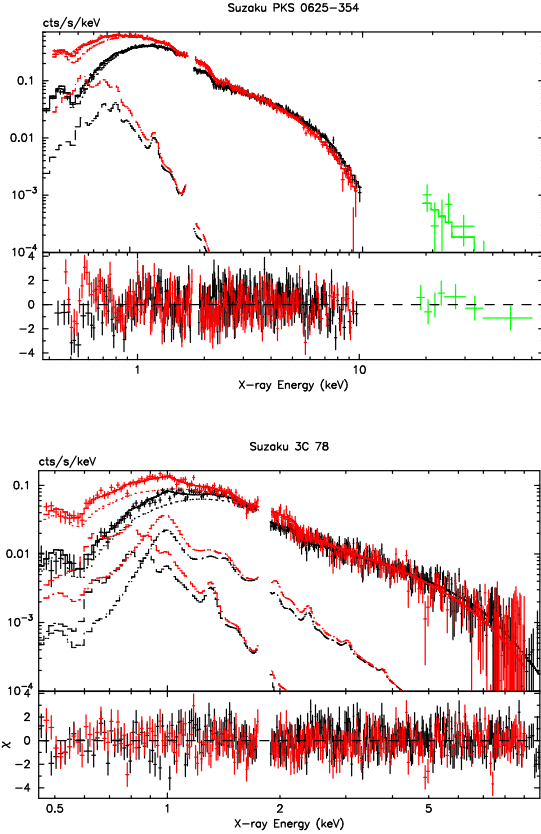


Figure 1: *Suzaku* spectra of PKS 0625–354 and 3C 78. The black, red, and green symbols are XIS-F, XIS-B, and HXD-PIN spectra, respectively. The solid line represents the best-fit total model, while the dashed and dotted lines are the *apec* and power-law model components, respectively. The bottom panels show the residuals in units of σ .

3. GeV Gamma-ray results and SED

We analyzed *Fermi* LAT 5 years data of PKS 0625–354 and 3C 78. For the analysis, LAT Science Tools version v9r32p5 was utilized with the P7REP_SOURCE_V15 Instrument Response Functions (IRFs). Both radio galaxies are clearly visible in the 0.2 to 300 GeV LAT counts maps. We extracted the data within a $12 \times 12 \text{ deg}^2$ rectangular region centered on each object. The binned likelihood fitting with the *gtlike* tool was performed. The field background point sources within 14.5° from each source, listed in the LAT 2 year catalog [Nolan et al. 2012], were included. The standard LAT Galactic emission model was used (*gll_iem_v05.fits*) and the isotropic diffuse gamma-ray background and the instrumental residual background were represented as a uniform background (*iso_source_v05.txt*). A like-

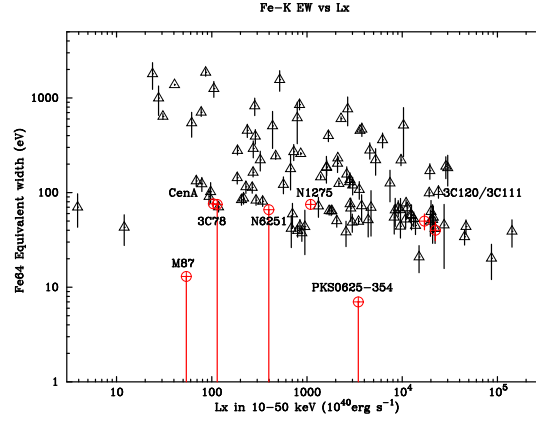


Figure 2: Fe-K line EW plotted against the X-ray luminosity for our sample of radio galaxies (red circles) and Seyfert galaxies (black triangles) analyzed by Fukazawa et al. [2011]. The data points with only the lower error bar represent upper limits.

likelihood analysis was performed with the energy information binned logarithmically in 30 bins in the 0.2–300 GeV band, and the spatial information binned with $0.15 \times 0.15 \text{ deg}^2$ bin size.

GeV gamma-ray spectra of both galaxies show a flat power-law with a photon index of 1.72 ± 0.06 and 2.01 ± 0.16 for PKS 0625–354 and 3C 78, respectively. Studies of time variability show a flare-like event for PKS 0625–354 and no significant variation for 3C 78. Figure 3 and 4 shows a SED of both galaxies, based on our *Suzaku* and *Fermi* data and other available data. SEDs are well modelled by the one-zone synchrotron self-Compton model from Finke et al. [2008]. Compared with other GeV-emitting radio galaxies whose results were also all done by the same model of Finke et al. [2008], lower bulk Lorentz factors of 2–6 are preferred when compared to those of typical blazars. An unique property of PKS 0625–354 and 3C 78 is a higher breaking energy of electron spectrum. This is attributed to higher SED-peaking energies of both galaxies (figure 3, 4). Considering this property, we plot the Synchrotron peak luminosity against the Synchrotron peaking frequency as shown in figure 5, where most of other data of blazars and radio galaxies are taken from Meyer et al. [2011]. For this plot, Meyer et al. [2011] states the high-E peaked objects are only the most aligned jet objects with radiatively inefficient accretion and decelerating weak jet. However, PKS 0625–354 and 3C 78 are outliers of this model, and thus they are at odds with the FR-I/BL Lac unification.

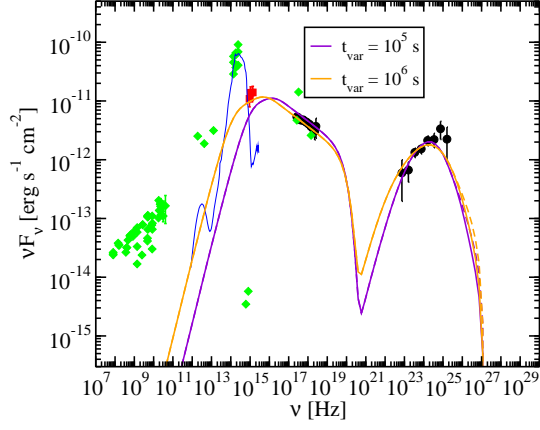


Figure 3: SEDs of PKS 0625–354 . Black circles indicate the *Suzaku* X-ray and *Fermi*-LAT γ -ray data presented in this paper, green diamonds are archival data. The thick curves denote the synchrotron/SSC model fits with two different variability timescales, as given in the legend. The solid curves include $\gamma\gamma$ absorption with the EBL model of ?, while the dashed curves do not. The thin

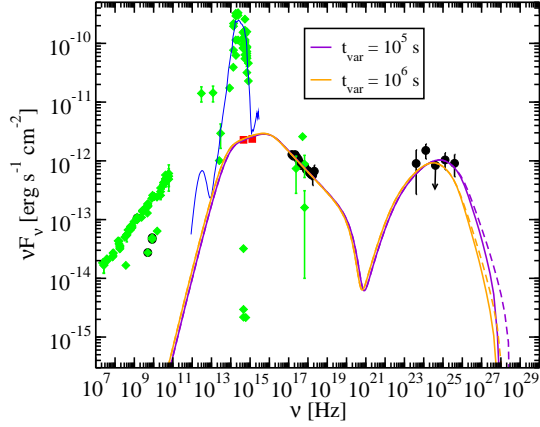


Figure 4: SEDs of 3C 78. Same as figure 3.

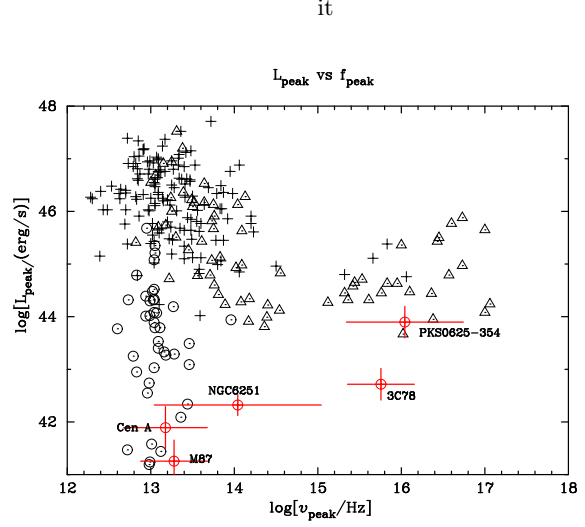


Figure 5: Relation between synchrotron peak frequencies and peak luminosities of PKS 0625–354 and 3C 78, together with other sources from our sample of radio galaxies (red circles). For a comparison, radio galaxies, BL Lacs, and FSRQs from Meyer et al. [2011] are also plotted (black circles, triangles, and crosses, respectively).

References

- Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, *Science*, 328, 725
- Finke, J. D., Dermer, C. D., Böttcher, M. 2008, *ApJ*, 686, 181
- Fukazawa, Y., Hiragi, K., Mizuno, M., et al. 2011a, *ApJ*, 727, 19
- Fukazawa, Y., Finke, J., Stawarz, L., et al. 2015, *ApJ*, 798, 74
- Meyer, E. T., Fossati, G., Georganopoulos, M., & Lister, M. L. 2011, *ApJ*, 740, 98
- Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, *ApJS*, 199, 31